Beam Transfers

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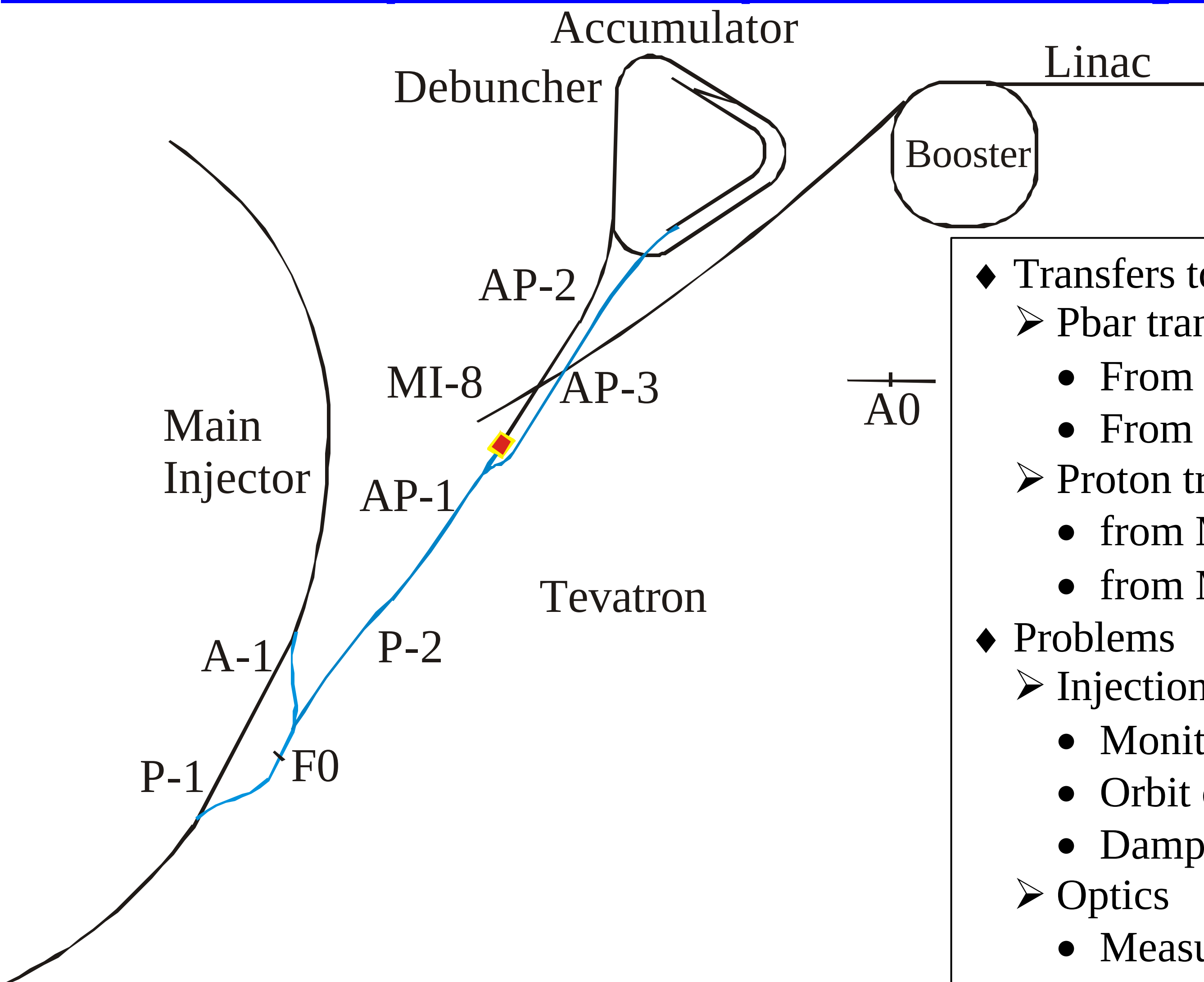
Talk outline

1. The status of beam transfers and the scope of the project
2. Sources of emittance growth
   a. Emittance growth due to injection oscillations
   b. Emittance growth due to betatron and dispersion mismatch
   c. Emittance growth due to X-Y coupling
3. MI to Tevatron transport for proton and antiproton beams
4. Accumulator to MI transport for 8 GeV antiproton beam
5. Transport from MI to the pbar production target
6. Improvements in reproducibility and reliability

   Conclusions

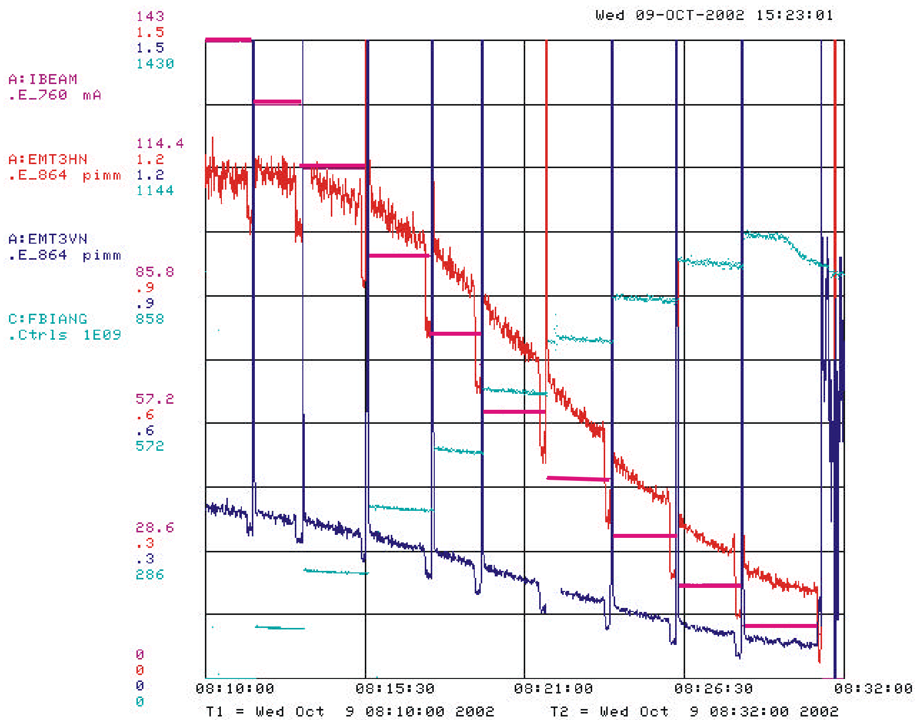
1. The Status of Beam Transfers and the Scope of the Project



The layout of transfer lines

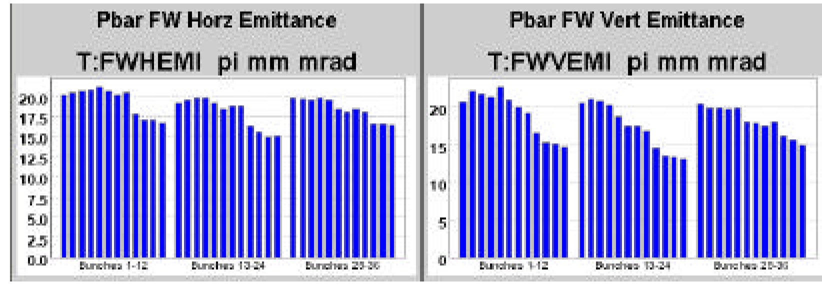
- ♦ Transfers to be improved
  - ➢ Pbar transfers
    - From Accumulator to MI, 8 GeV
    - From MI to Tevatron, 150 GeV
  - ➢ Proton transfers
    - from MI to Tevatron, 150 GeV
    - from MI to target, 120 GeV
- ♦ Problems
  - ➢ Injection oscillations
    - Monitoring
    - Orbit closure correction
    - Damping
  - ➢ Optics
    - Measurements
    - Correction

Antiproton emittances in Accumulator and Tevatron (Shot 1836, 10/09/02, $33 \cdot 10^{30}$ cm^{-2}s^{-1})

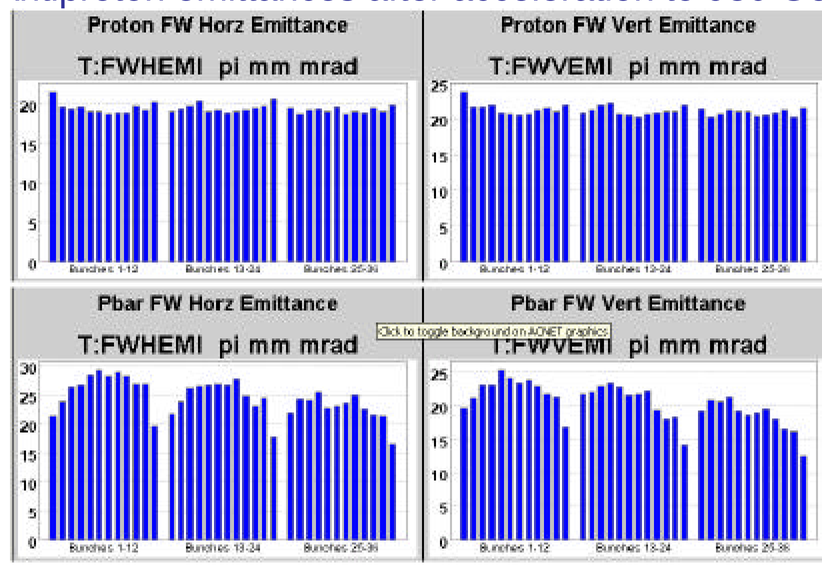


Pbar beam emittance variations during shots

	Initial	Final
Time, min	0	17
Accum. Beam Current, mA	143	11
Accum. hor. emittance, mm mrad	10.9	2.9
Accum. vert. emittance, mm mrad	3.8	1
Tot. pbar Δp/p in 8 GeV line	±.037%	±.063%
Transfer eff. to Tev. at injection		74%



Antiproton emittances after acceleration to 980 GeV



Proton and antiproton emittances at collisions

- The average antiproton emittances
  - 6 mm mrad – in accumulator
  - 17 mm mrad after acceleration in Tevatron
  - 23 mm mrad – at collisions
- Transfer efficiency from Acc. to HEP – 68%

Antiproton emittances in Accumulator and Tevatron (continue)

- The balance of the emittance growth
  - Transfer from Accumulator to MI ~2 mm mrad
  - MI acceleration + coalescing ~2 mm mrad
  - Transfer from MI to Tevatron ~7 mm mrad

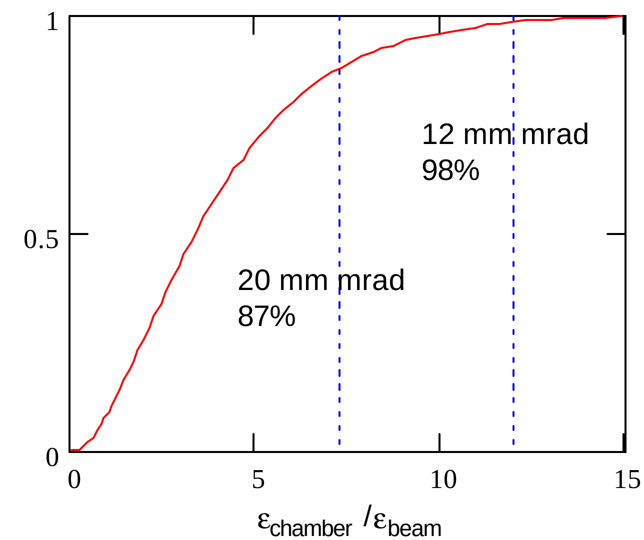
(6+2+2+7=17)+(**Beam-beam** ~5?) ~22 **mm mrad**

Status and projections for the beam transfers

	Line	Energy [GeV]	October 2002		Goal (~June 2003)	
			$\varepsilon_{in} / \varepsilon_{fin}$ * [mm mrad]	Transfer efficiency	$\varepsilon_{in} / \varepsilon_{fin}$ * [mm mrad]	Transfer efficiency
Accumulator to MI, $\bar{p}$	AP3-P1	8	6 / 8	97%	7** / 8	>99%
MI to Tevatron, $\bar{p}$	A1	150	10/17	99%***	10 / 12	99%
MI to Tevatron, p	P1	150	21/24	99%	21 /23	99%
MI to the target, p	P1-AP3	120	Beam size at target σ =200 μm		Beam size at target σ =130 μm	

* $\varepsilon \equiv (e_x + e_y)/2$; ** 170 mA pbar stack;
*** calibration uncertainty ~3-5%

- Pick luminosity rises with emittance decrease due to
  - Beam current increase due to increase of beam life time at the injection and top energies
  - Smaller beam size at collisions
- Presently, major contribution to the antiproton beam emittance growth comes from the beam transfers
  - Accumulator to MI transfer was improved in Feb.02
  - MI to Tevatron transfer for antiprotons is a major issue for this fall. First results are already visible.
    - Reducing pbar emittance in the Tevatron from ~20 mm mrad to ~12 mm mrad should decrease the beam loss at the acceleration and squeeze from ~12% to ~2%



2. Sources of emittance growth

a. Emittance Growth due to Injection Oscillations

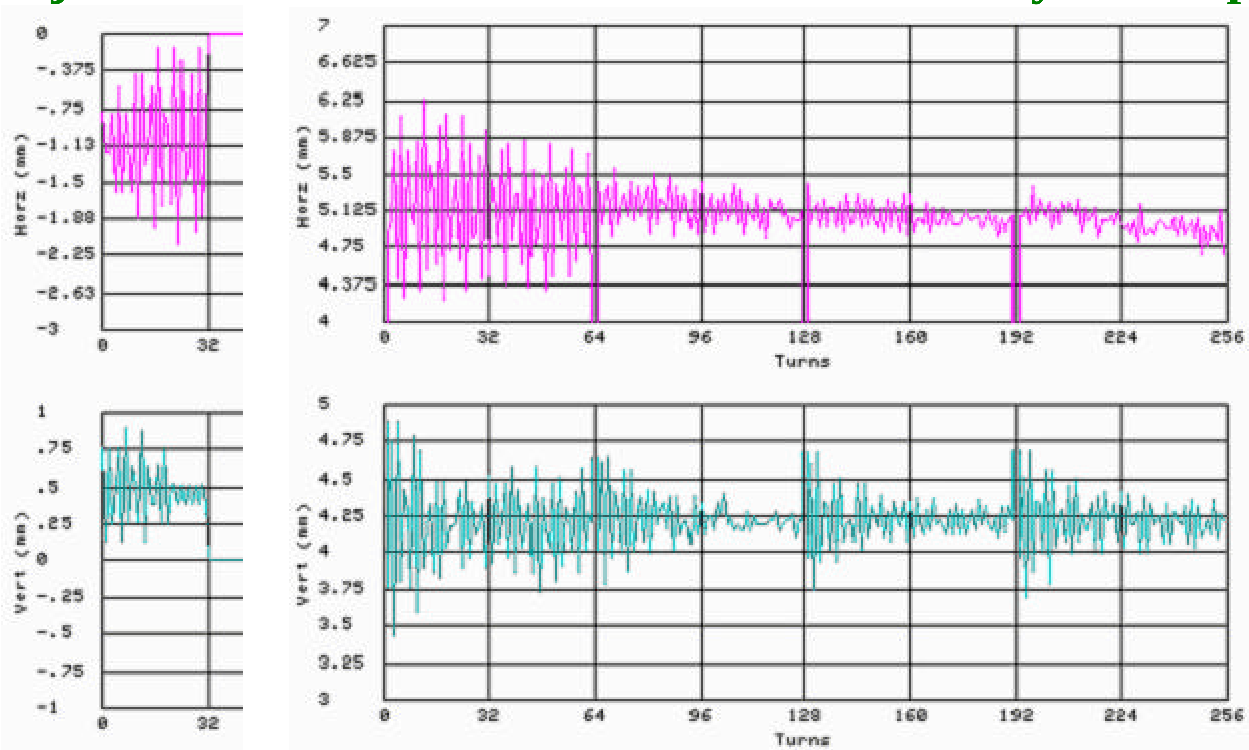
$$e' = e + \frac{1}{2}\left(bx'^2 + 2axx' + gx^2\right) \qquad \text{or} \qquad e' = e + \frac{1}{2}\frac{x_{\max}{}^2}{b}$$

	b_x / b_x [m]	Present performance		Goal		
		A_x/A_y [mm]	$\Delta\varepsilon_x/\Delta\varepsilon_y$ [mm mrad]	A, [mm] no damper	A, [mm] with damper	$\Delta\varepsilon$ [mm mrad]
Accumulator to MI, $\bar{p}$	55 / 55	1 – 2	0.5 – 2	< 0.7	3	< 0.25
MI to Tevatron, $\bar{p}$	103 / 62 *	0.5 – 1	1.2–4.7/ 1.9–7.7	< 0.25	1.5	< 0.5
MI to Tevatron, p	103 / 62 *	0.25–0.5	0.3–1.2/0.48–1.9	< 0.25	1.5	< 0.5

* beta-functions at Tevatron BLT

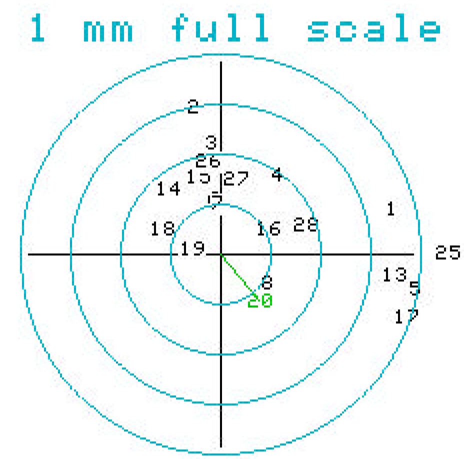
- **Sources of injection oscillations**
  - Initial injection errors
  - Shot-to-shot field variations in dipoles, dipole correctors and kickers
  - Bunch-to-bunch field variations in correctors for both pbar transfers
- **Ways to implement good quality of transfers**
  - Orbit closure before colliding bunches are injected
  - Orbit closure correction for every new injection
    - Injection damper in the future
- **Turn-by-turn BPM measurement for every injected bunch confirms transfer quality**

Injection oscillations in Tevatron measured by the scope based BLT (McGinnis)

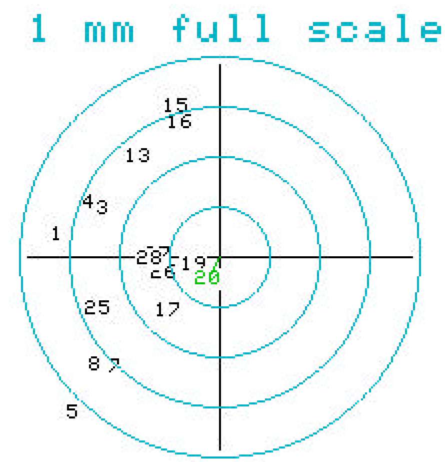


Bunch 1 Bunch 1 Bunch 2 Bunch 3 Bunch 4

Protons ________________Antiprotons________________



Horizontal



Vertical

	Amplitude of oscillations [mm]		Corresponding emittance growth [mm mrad]	
	Hor.	Vert.	Hor.	Vert.
Protons	1	0.5	4.6/2=2.3*	2/2=1*
Antiprotons	1	0.7	4.6	3.7

* factor of 1/2 appeared because the horizontal motion of protons (above picture) is excited by X-Y coupling

Injection dampers

Transfer type	Maximum initial oscillations [mm]	Damping time, N_{damp} [turns]	Decoherence time, N_{decoh} [turns]	Emittance growth suppression, κ	$\Delta\varepsilon$ [mm mrad]
Accumulator to MI, $\bar{p}$	3	70	>200	0.1	< 0.4
MI to Tevatron, p & $\bar{p}$	1.5	30	>200	0.03	< 0.5

$$\Delta e = k\ \Delta e_0 \quad , \qquad k \approx \left(\frac{N_{damp}}{N_{decoh}} \right)^2 \quad , \quad \Delta e_0 = \frac{1}{2} \frac{a_{\max}{}^2}{b}$$

Main parameters of Tevatron injection damper

Type	Bunch-by-bunch
Kick duration	<200 ns
Bunch frequency	2.5 MHz
Peak power	5 kW
Beta-function at kicker [m]	80
Kicker length	1 m
Kicker gap	7.5 cm

Tevatron damper is expected to be commissioned in March-April 2003

2. Sources of emittance growth (continue)

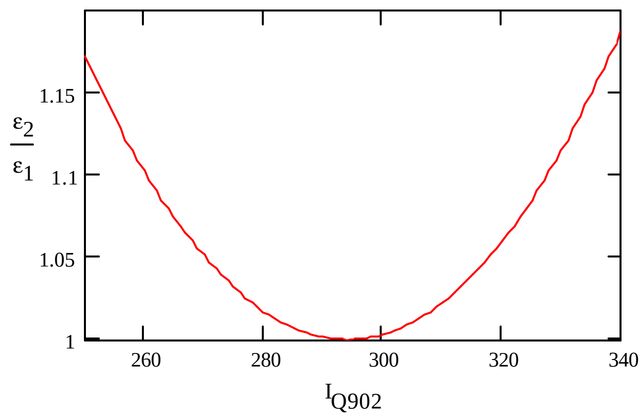
b. Emittance Growth due to Betatron and Dispersion Mismatch

Emittance growth from a lattice with β_1, α_1, D_1 and D_1' to a lattice with β_2, α_2, D_2 and D_2' is

$$\varepsilon' = \frac{\varepsilon}{2}\left(\frac{\beta_1}{\beta_2}\left[1+\alpha_2^{\,2}\right]+\frac{\beta_2}{\beta_1}\left[1+\alpha_1^{\,2}\right]-2\alpha_1\alpha_2\right)+\frac{\sigma_p^{\,2}}{2}\left(\beta_2\left(D_0'-D_1'\right)^2+2\alpha_2\left(D_0'-D_1'\right)\left(D_0-D_1\right)+\frac{\left(D_0-D_1\right)^2}{\beta_2}\left(1+\alpha_2^{\,2}\right)\right)$$

Emittance growth due single quad focusing error at zero dispersion

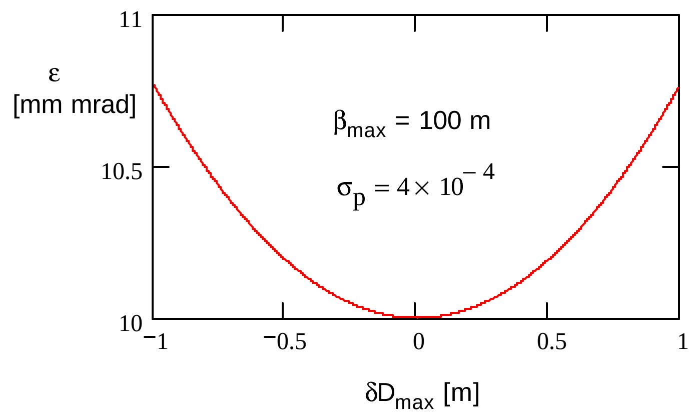
$$\varepsilon_2 \approx \varepsilon_1\left(1+\frac{\delta\alpha^2}{2}\right)\approx \varepsilon_1\left(1+\frac{\left(\beta\delta F\right)^2}{2F^4}\right)$$



- Differential orbit measurements allow seeing focusing errors of 1-2%.
  - It is sufficient to tune the line focusing so that the emittance growth would be below 10%.
  - Further improvement is expected from online tuning with orthogonal quads.

Requirements for dispersion mismatch for MI to Tevatron transfer

$$\varepsilon_2 \approx \varepsilon_1\left(1+\frac{\left(\sigma_p\delta D_{\max}\right)^2}{2\beta_{\max}}\right)$$



- Dispersion mismatch below about 0.5 m does not produce significant emittance growth

2. Sources of emittance growth (continue)

c. Emittance Growth due to X-Y Coupling

Emittance growth for beam transfer from an uncoupled lattice with b_x, a_x, b_y and a_y, to a coupled lattice described by b_{1x}, a_{1x}, b_{1y}, a_{1y}, b_{2x}, a_{2x}, b_{2y} and a_{2y} with the eigen-vectors

$$\mathbf{v}_1 = \begin{bmatrix} \sqrt{b_{1x}} \\ -\dfrac{i(1-u)+a_{1x}}{\sqrt{b_{1x}}} \\ \sqrt{b_{1y}}e^{in_1} \\ -\dfrac{iu+a_{1y}}{\sqrt{b_{1y}}}e^{in_1} \end{bmatrix} \quad , \qquad \mathbf{v}_2 = \begin{bmatrix} \sqrt{b_{2x}}e^{in_2} \\ -\dfrac{iu+a_{2x}}{\sqrt{b_{2x}}}e^{in_2} \\ \sqrt{b_{2y}} \\ -\dfrac{i(1-u)+a_{2y}}{\sqrt{b_{2y}}} \end{bmatrix}$$

is determined by the following equations:

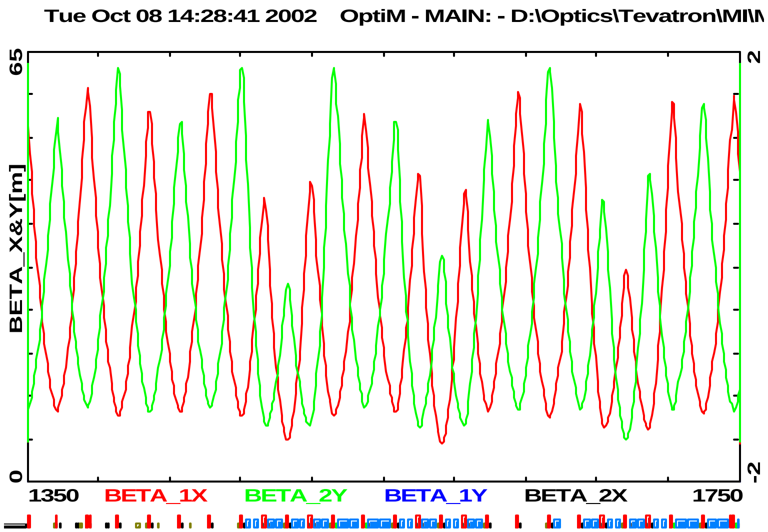
$$e_1' = e_1 A_{11} + e_2 A_{12}$$
$$e_2' = e_1 A_{21} + e_2 A_{22}$$

$$A_{11} = \frac{1}{2}\left(\frac{b_x}{b_{1x}}\left[(1-u)^2 + a_{1x}^2\right] + \frac{b_{1x}}{b_x}\left[1 + a_x^2\right] - 2a_{1x}a_x \right) \quad , \qquad A_{12} = \frac{1}{2}\left(\frac{b_y}{b_{1y}}\left[u^2 + a_{1y}^2\right] + \frac{b_{1y}}{b_y}\left[1 + a_y^2\right] - 2a_{1y}a_y \right)$$

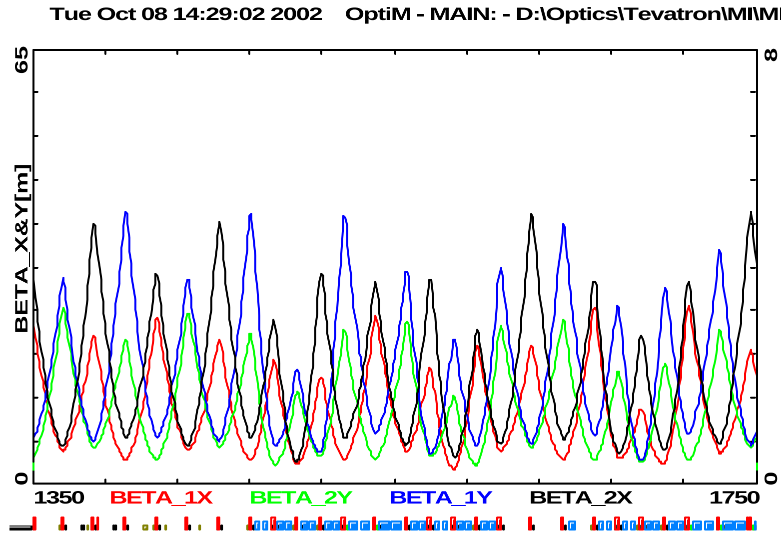
$$A_{21} = \frac{1}{2}\left(\frac{b_x}{b_{2x}}\left[u^2 + a_{2x}^2\right] + \frac{b_{2x}}{b_x}\left[1 + a_x^2\right] - 2a_{2x}a_x \right) \quad , \qquad A_{22} = \frac{1}{2}\left(\frac{b_y}{b_{2y}}\left[(1-u)^2 + a_{2y}^2\right] + \frac{b_{2y}}{b_y}\left[1 + a_y^2\right] - 2a_{2y}a_y \right)$$

Coupling Example: Very strong coupling in Main Injector

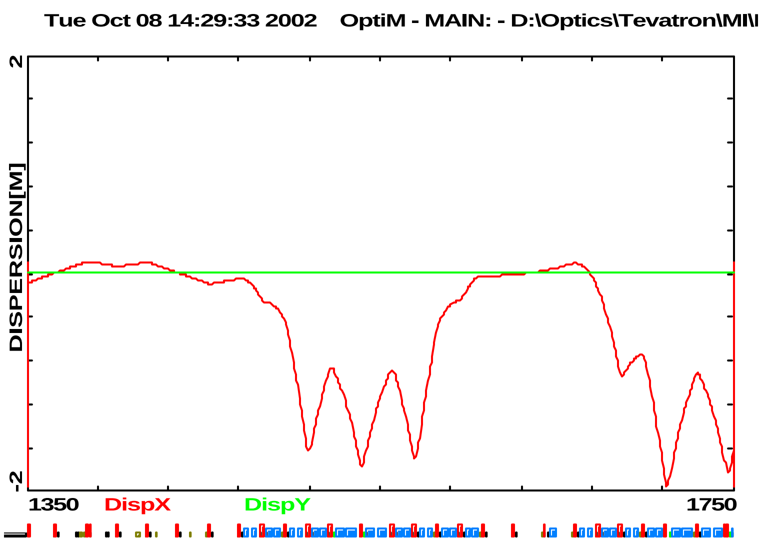
Uncoupled Lattice

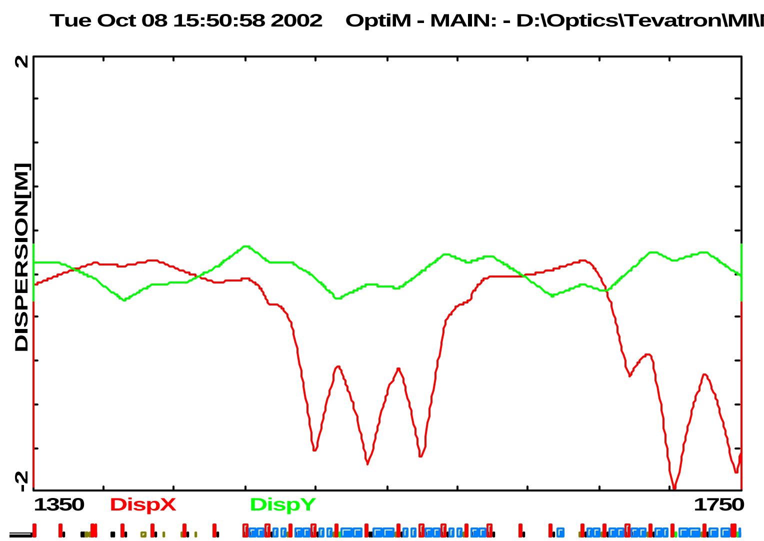


Coupled lattice GdL_{SQ335}=15.2 kG (3% of general quad)



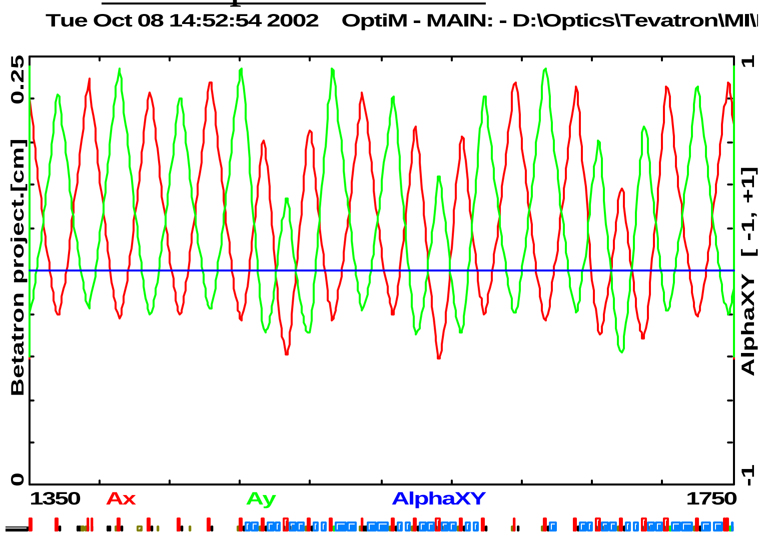
Beta-functions



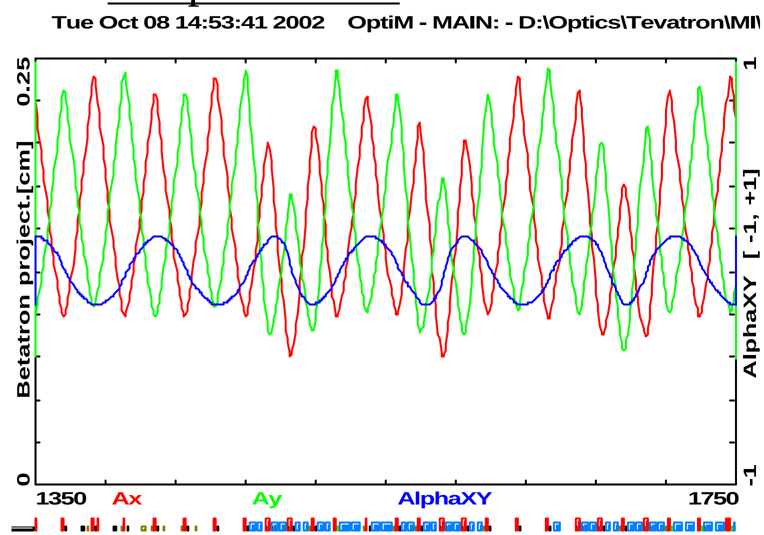


Dispersions

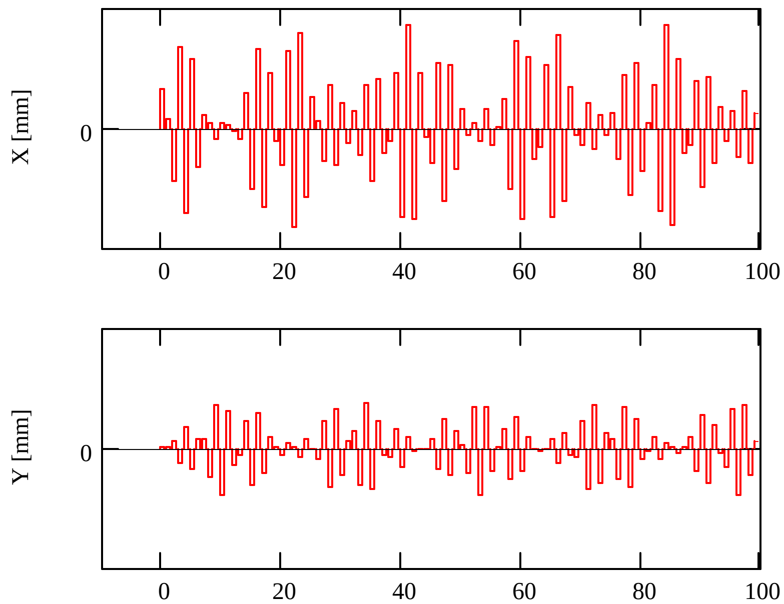
Uncoupled Lattice



Coupled lattice



Beam sizes



- Strong coupling is created by a weak skew quad because of small tune split (ΔQ=0.010 $\Rightarrow$ 0.045)
- Coupling strongly changes beta-functions and turn-by-turn beam positions
- But it makes little change for the beam envelopes and dispersions
- There is negligible emittance growth if $\varepsilon_1=\varepsilon_2$

$$e_1' = 0.400 \cdot e_1 + 0.608 \cdot e_2$$

$$e_2' = 0.611 \cdot e_1 + 0.403 \cdot e_2$$

3. MI to Tevatron Transport for Proton and Antiproton beams

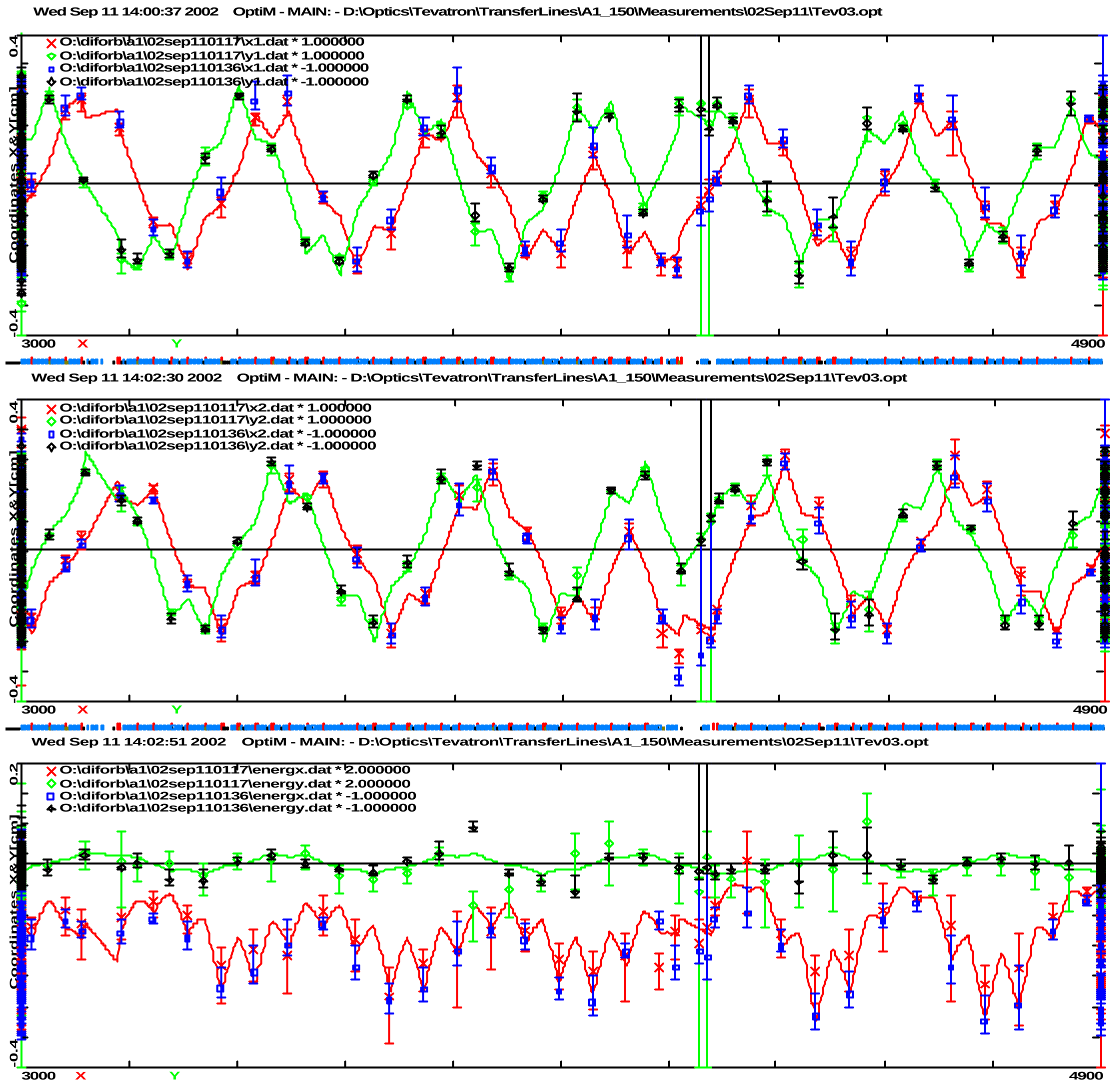
Emittance growth measurements for the MI-Tevatron-MI beam round trip with MI flying wires

- This measurements does not rely on relative calibration of different emittance monitors
  - More reliable measurements for the total emittance growth because the same device is used for both measurements
  - Cannot distinguish which transfer is responsible for the emittance growth
  - MI flying wires make more reliable emittance measurements because they are installed at place with zero dispersion
- Emittance measurement allows one to observe the emittance growth but they do not specify what kind if mismatch is responsible for the growth
- **Status in August 02 and Presently**

	Initial value [mm mrad]	Final value, Aug.02 [mm mrad]	Final value, Oct 02 [mm mrad]
Vertical emittance	~12	~15	~14=12+**2**
Horizontal emittance	~12	~20	~15=12+**3**

- **The goal**
  - To reduce the round trip emittance growth **below 2 mm mrad**

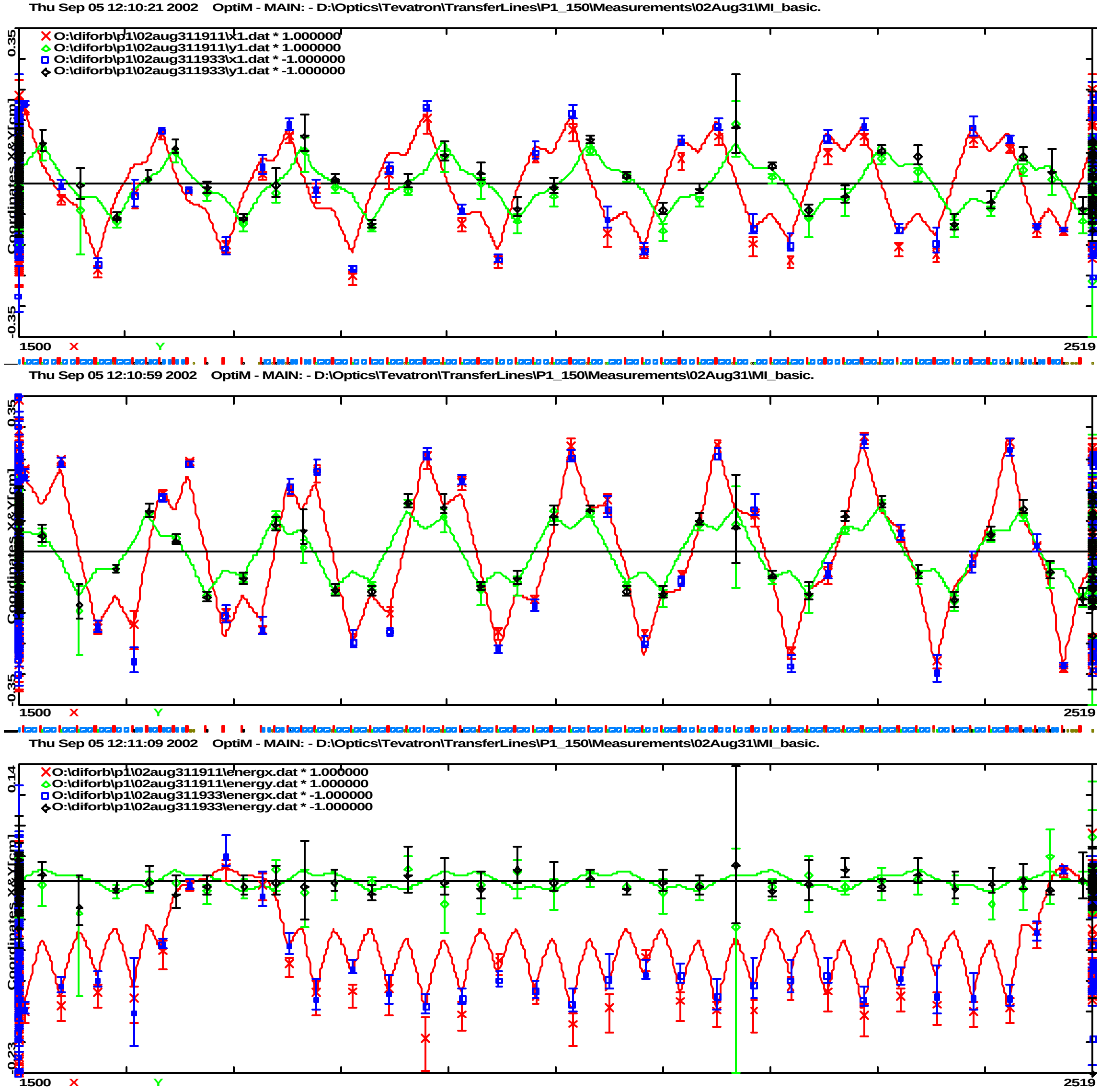
Results of Differential orbit measurements for Tevatron at pbar helix



Differential closed orbit measurements in vicinity of F0 Tevatron section. Tevatron Lambertson position is marked by vertical lines straight section

- Good coincidence between the model and the measurements
  - Measured horizontal dispersion coincides with design within 10%
  - There is considerable coupling at pbar helix
    - $D_{y_{\max}} \approx 35$ cm
  - Indirect evidence that the beam envelopes coincide with the design within 10%
- Good quality BPM measurements
  - Both differential orbit measurements for correctors and energy change exhibit that Tevatron BPMs underreport actual beam displacement by ~8%.
- Used beam excitation
  - Correctors 50 μrad
  - Energy correction of 0.054% corresponds to 80 Hz at T:VFKNOB

Results of Differential orbit measurements for Main Injector

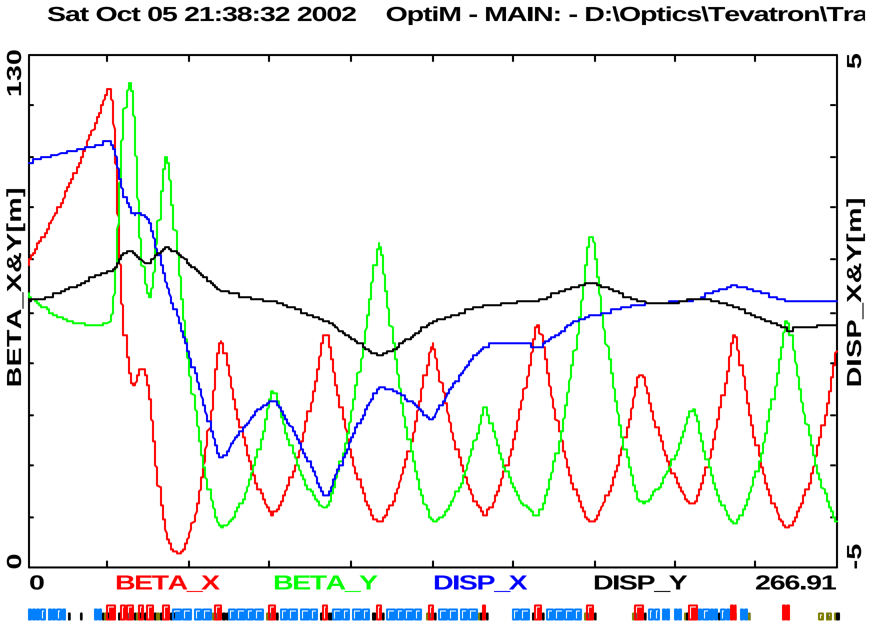


Differential orbits in MI before proton extraction point

- ♦ Decent coincidence between the model and the measurements
- ♦ BPM measurements are good in vicinity of proton extraction point
  - ➢ But there are large groups of BPMs which do not make reliable measurements
    - We are investigating the source of the problem

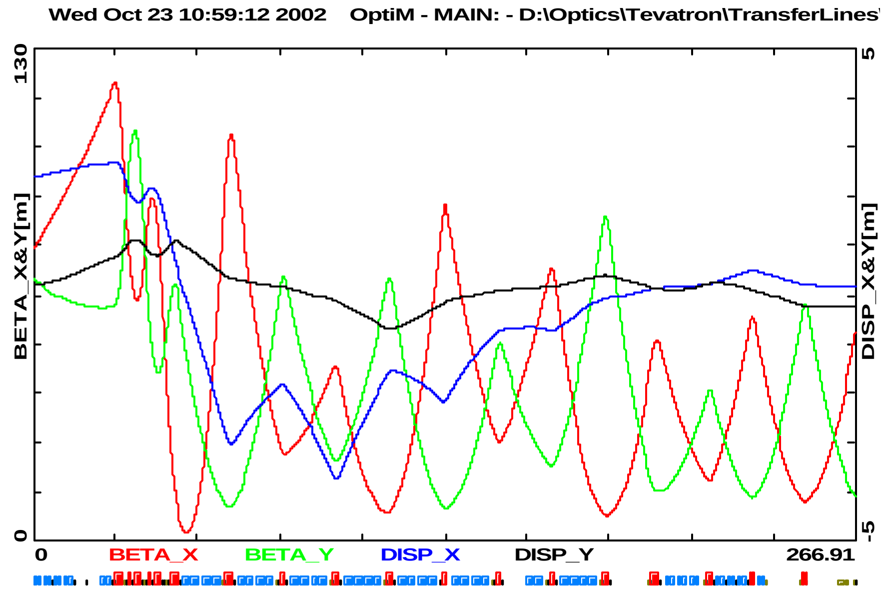
Constraints on optics adjustments for A1 and P1 lines

♦ 8 power supplies - 8 parameters + limitations on beta-functions and power supply currents



A1 line optics introduced in Sep/30/02; first four quads are combined into two pairs

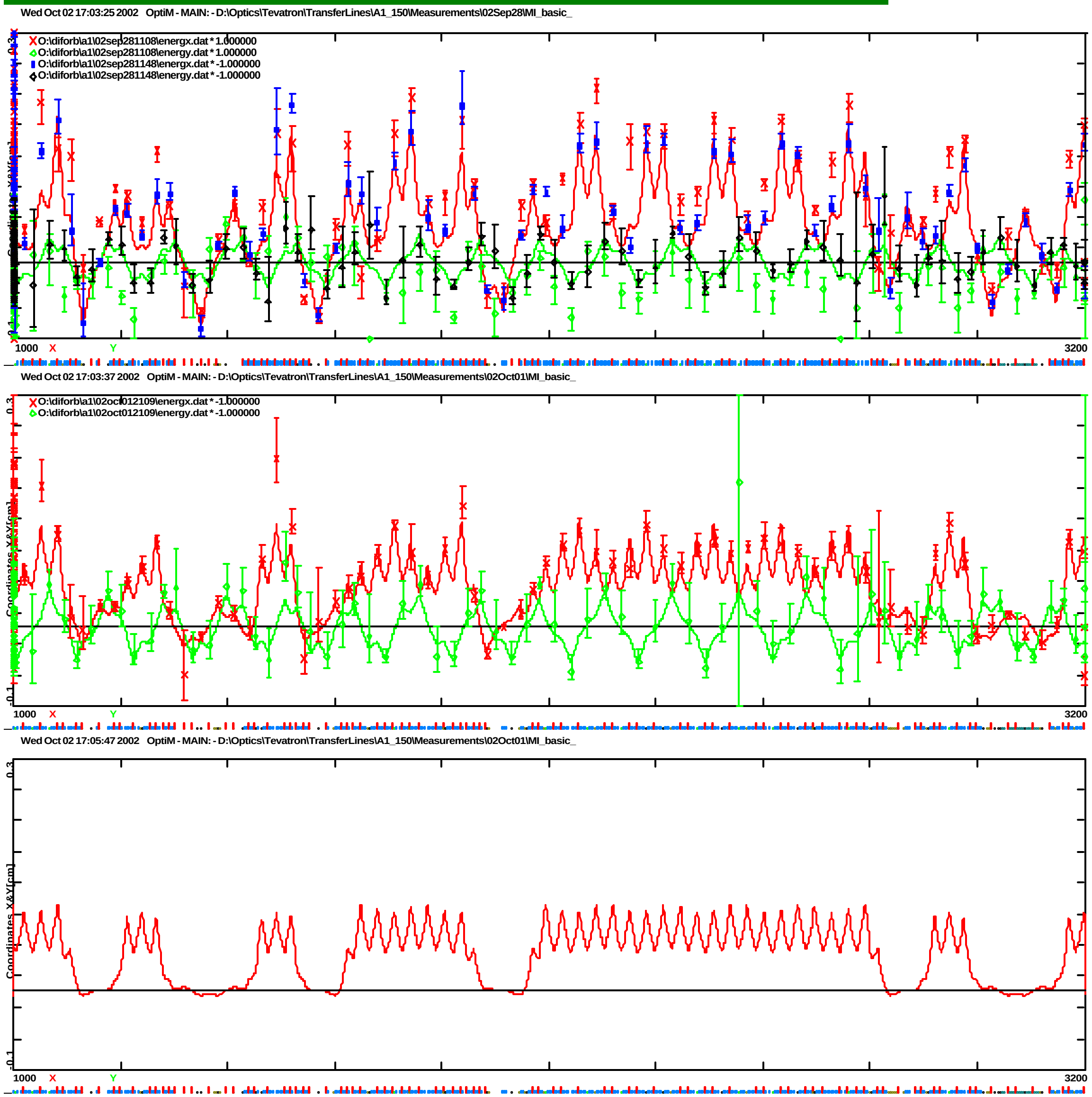
- 6 independent parameters
- Small beta-functions
- Insufficiently good match for both dispersions



Final A1 optics; all available power supplies are independent

♦ 8 independent parameters
♦ Improved match for envelopes and dispersions
♦ Match for vertical dispersion is limited by
  ➢ Constraints on currents of power supplies
  ➢ The growth of beta-functions
♦ Peak of the first turn vertical dispersion mismatch in Tevatron is about 0.7 m. That yields the emittance growth of 0.5 mm mrad

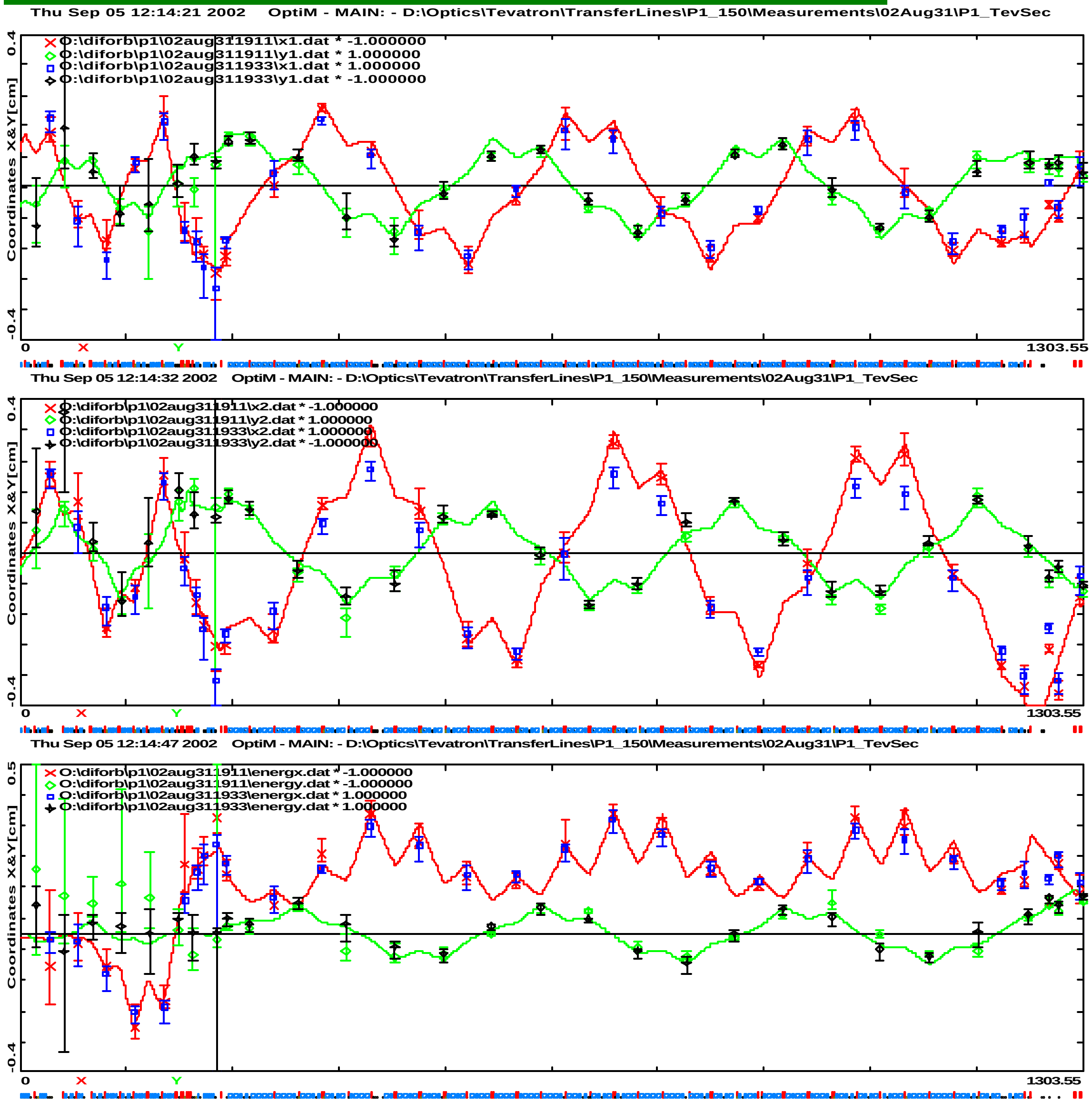
Present status of A1 line optics and plans



First turn dispersions measured in MI with reverse protons before and after Sep.30 and MI dispersions (bottom)

- Horizontal dispersion mismatch was significantly decreased at Sep.30 optics change
- Currently dispersion mismatch contributes
  - $\Delta\varepsilon_x \approx 0.5$ mm mrad ($\Delta D_x \approx 0.7$ m)
  - $\Delta\varepsilon_y \approx 1.1$ mm mrad ($\Delta D_y \approx 1.1$ m)
- New already tested optics should reduce emittance growth due to optics mismatch below 1 mm mrad
  - Steps to establish New optics
    - Download new settings
    - Perform differential orbit measurements
    - Analyze measurements and correct the model. Match the transfer line optics to measured dispersions
    - Download corrections
    - Perform the fine tuning of beam envelopes with orthogonal quads and flying wires emittance monitors

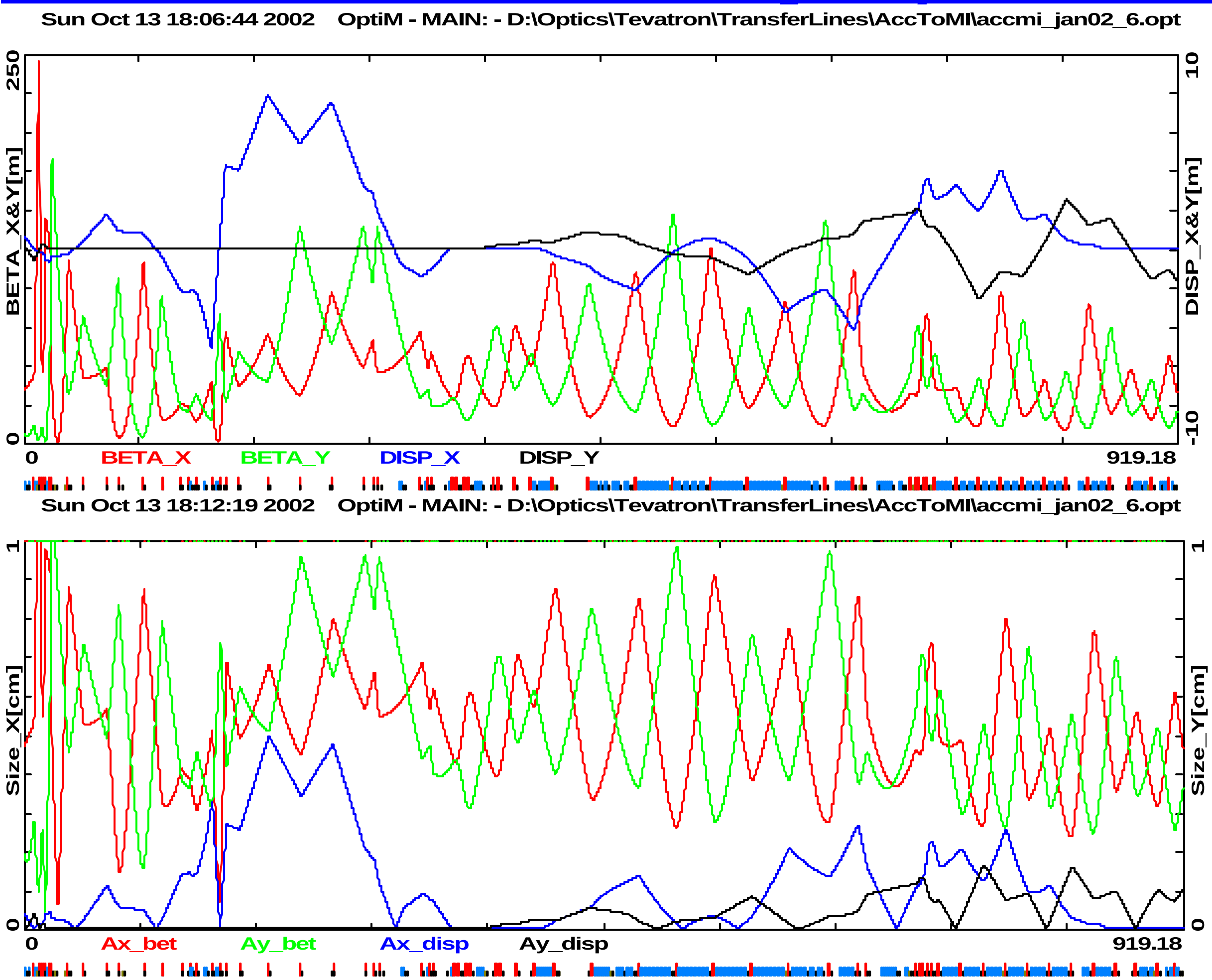
Present status of P1 line optics and plans



Differential orbits in P1 line and Tevatron sector F

- Focusing in P1 line is well described by the model
- Currently dispersion mismatch contributes
  - $\Delta\varepsilon_x \approx 1.1$ mm mrad ($\Delta D_x \approx 1.1$ m)
  - $\Delta\varepsilon_y \approx 1.7$ mm mrad ($\Delta D_y \approx 1.3$ m)
- Similar to A1 line optics we plan to introduce new optics for P1 line
  - Better dispersion match
  - It should reduce emittance growth due to optics mismatch below 1 mm mrad

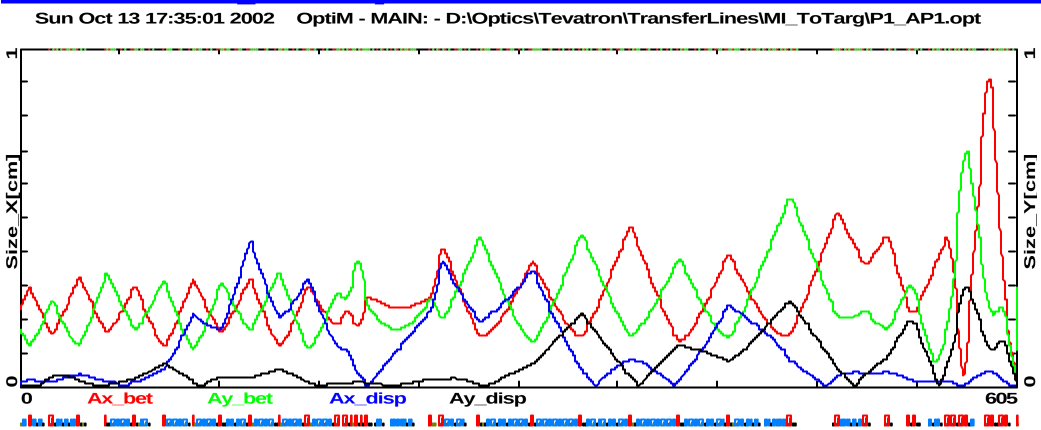
4. Accumulator to MI transport for 8 GeV Antiproton Beam

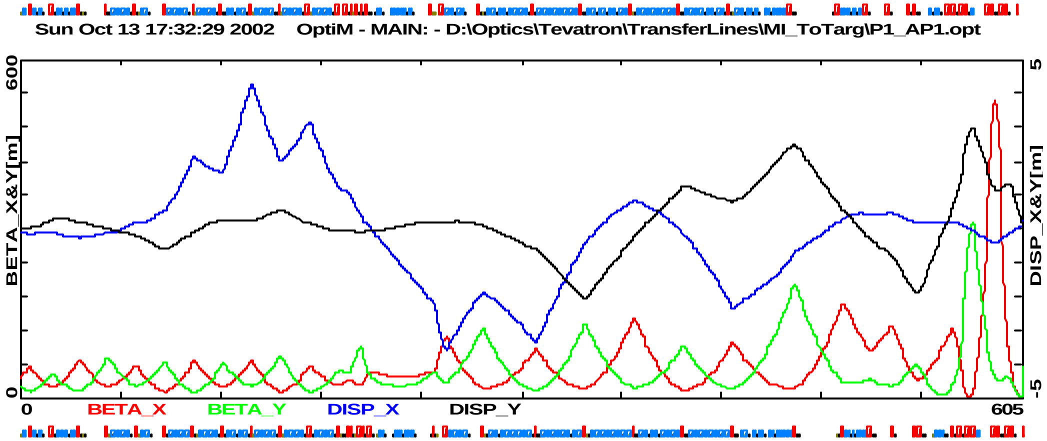


Beta functions dispersions and beam envelopes for the Accumulator to MI transfer, ε=6 mm mrad, $\Delta p/p$=0.063%

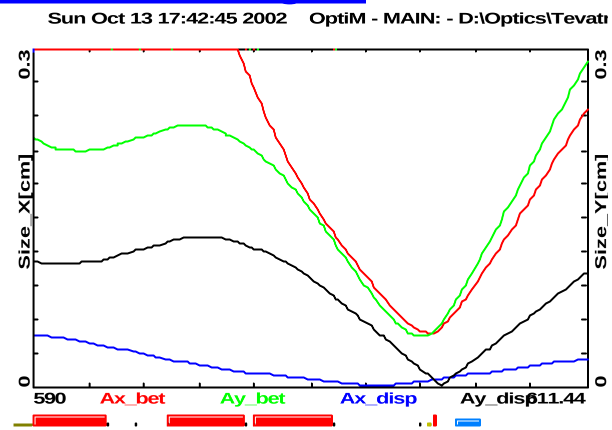
- Optics was corrected and tuned in the spring of 2001
- Design has $D_y \neq 0$ at injection into MI
  - negligible increase of the vertical emittance, $\Delta\varepsilon_y$=0.25 mm mrad
- Ionizing radiation limit in Antiproton source buildings constraints the beam intensity
  - Long measurements
  - Poor accuracy
- Limited accuracy of optics measurements
  - Large quad adjustments for fine optics tuning
- Careful optics measurements and data analysis
  - should decrease beam envelopes
  - and bring more reliable beam transport

5. Transport from MI to the Pbar Production Target





Beam sizes (ε=20 mm mrad and $\Delta p/p_{tot}$=0.1%), and beta-functions dispersions



- Optics was corrected and tuned at the end of 2001
- Design at target
  - $D_y = 0, \quad D'_y \neq 0$
  - $\sigma_x = \sigma_y$ =185 μm for ε=20 mm mrad
- Measurements: $\sigma_x \approx \sigma_y \approx$200 μm
- We would like to decrease the beam size on the target to about 130 μm
  - To avoid aperture limitations in the line we will need to make better steering at the end of the line

6. Improvements in Reproducibility and Reliability

- **8 GeV accumulator to MI transfers**
  - Introducing hysteresis protocol for AP1 and AP3 magnets
  - Putting Hall probes into a few AP-1quadrupoles to monitor short and longtime drifts
  - Quadrupole pickup in Accumulator to monitor the beam envelope mismatch
  - Injection damper in MI
- **MI to Tevatron MI transfers**
  - Injection dampers
  - Improvements for BLT
    - Better resolution
    - Additional software
      - Bunch injection amplitudes in all 3 planes (x, y, s)
      - Bunch tunes
      - Bunch chromaticities

Conclusions

- Injections errors have been a leading reason of the antiproton beam emittance growth
  - Introducing turn-by-turn measurements for every bunch injected into Tevatron allowed us to improve orbit closure. That yielded significantly improvement for beam transfers
  - Further improvements are expected with the orbit closure
  - Tevatron injection damper (April 2003) will eliminate the problem and will make reliable transfers
- First optics correction in A1 line brought better transfers and luminosity increase
  - Further optics improvements are expected to reduce the beam emittances by 1-2 mm mrad for each transfer
  - Stronger coupling in Accumulator can further reduce horizontal emittance and improve transfer quality
- Only minor improvements can be done to reduce the collider filling time
  - But significant improvements can be done
    - to improve reproducibility and reliability of shots
    - to shorten total shot setup time
- We plan to carry out the most of transfer improvements by the middle of 2003
- Adding Recycler into collider operations
  - will alleviate the Accumulator to MI transfers due to additional cooling in Recycler
  - will transfer many steps of shot setup from Accumulator to Recycler